Environmental Impacts of Precipitation Management: Results and Inferences from Project Skywater

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Abstract

Recent completion of several research projects into weather modification impacts on the environment provides an opportunity for placing this subject in a new perspective. Studies of physical and biological processes relating precipitation and ecosystem changes show relatively few discernible effects, all of them minor in nature and magnitude. Direct effects of nucleating agents no longer appear consequential. Since no acute problems have surfaced, the focus is likely to shift to possible long-term effects on ecosystems as a whole, where changes associated with natural precipitation gradients and climatic fluctuations provide a model for those to be expected from precipitation management. The weakness of environmental impacts of weather modification compared to the consequences of other human actions renders it unlikely that these impacts will be decisive within a behavioral framework.

1. Introduction

Following issuance of the report of the Special Commission on Weather Modification of the National Science Foundation (1966), investigation of environmental impacts became a recognized part of Project Skywater's program for developing an acceptable as well as an effective technology of precipitation management. A problem analysis undertaken for Skywater by Cooper and Jolly (1969) was followed by three major field programs of environmental research—one completed in 1975 (Knight, 1975) and two in 1976 (Steinhoff and Ives, 1976; Armstrong and Ives, 1976)—and by several analytical studies of agricultural and economic impacts. In addition, a Programmatic Environmental Statement for Project Skywater (Bureau of Reclamation, 1976a) is scheduled for distribution in mid-1977.

These several reports provide the basis for a new assessment not only of the environmental impacts of the Skywater program but also of the widespread and prolonged application of the two precipitation management technologies with which it is concerned—winter-orographic snowpack enhancement and summer-convective shower stimulation in the mountains and the Great Plains of the western United States, respectively. The review that follows is addressed to the impacts of these two technologies (which are jointly referred to as precipitation management) as distinguished from other developing and potential technologies, such as hail suppression and the modification of tropical maritime clouds, and from other precipitation technologies, such as winter-nonorographic cloud seeding.

Field activities of Project Skywater with potential for environmental impacts have run at a typical rate during the past decade of 100–300 modification-days per year (summed over all projects) over study areas typically from 3000 to 10 000 km^2 in extent. The most important have been the San Juan, Pyramid Lake, Wasatch, Bridger, and Jemez winter-orographic projects and the North Dakota, South Dakota, and High Plains Cooperative Program (HIPLEX) summer-convective projects. Other field activities were of shorter duration, less intensive operation, or smaller extent and dispersed relatively small quantities of seeding material.

Environmental studies under Skywater, totaling nearly $3 million, are shown in Table 1. Following the problem assessment by Cooper and Jolly, two groups of studies were planned. The first, addressed to physical and biological effects, was planned in cooperation with a group of advisors assembled under the leadership of Colorado State University (Teller *et al.*, 1970) and led to the establishment of three major field investigations—the San Juan and Medicine Bow Ecology Projects and the Avalanche Research Project—and a few minor experimental projects of a supporting nature. The second group of studies was addressed to economic and social impacts, necessarily of a more analytic nature since direct intervention with the economic and social systems that might be affected by precipitation management was not possible.

In addition to these programs, minor studies have been completed in support of the Sierra Cooperative and HIPLEX programs. In November 1976, Skywater sponsored a week-long interdisciplinary conference at Vail, Colo., devoted to all major aspects of precipitation modification impact, which included a nested conference on seeding agents cosponsored by the National Science Foundation.

2. Impact of widespread and prolonged applications of precipitation management

Far less concern has been expressed over the effects of Skywater and other field experiments than over the possible impacts of the widespread and prolonged precipitation management programs that would presumably follow successful conclusion of them. Indeed, the greater part of current studies focuses upon this broader question, even though Skywater has been and continues to be a program of technological development without authorization for operational applications.

Expectations of impact from widespread and prolonged application are based on a set of explicitly stated

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assumptions as to where, when, and with what intensity such management will be practiced at some future time when it is approaching technological maturity. The assumptions that underlay the present assessment are the following:

1) Only augmentation of winter-orographic snowpack and summer-convective showers are considered, since these are the technologies that Skywater is developing and that appear likeliest for widespread application.
2) State and federal laws will govern the conduct of precipitation management programs. These laws will, at a minimum, provide for qualification of persons in charge of operations and for specific constraints on operations in the face of perceived risks such as flood and avalanche. Proposals for particular projects will be required to pass the scrutiny of environmental impact assessment. Major federal programs will require congressional authorization and be subject to congressional review.
3) Applications intended to increase water supply for municipal, industrial, irrigation, and other off-channel uses will take place frequently in the precipitation accumulation regions of basins in which current withdrawal uses exceed or nearly equal expected 1980 dependable supply. They will take place only occasionally, and much less extensively, in regions where dependable supply substantially exceeds anticipated off-channel withdrawal uses.
4) Applications related to hydroelectric power will take place frequently in watersheds where the energy value of water is high and seldom where this value is low. They will tend to occur where installed capacity substantially exceeds average generation.
5) Applications related to in-channel nonwithdrawal

TABLE 1. Skywater-sponsored environmental research.

Contractor	Purpose	Period of Activity	Funding, $
Rocky Mountain Forest and Range Experiment Station, Forest Service	Behavior of runoff from increased snowpack in forest environment	Nov. 1964–June 1968	437 500
University of Michigan	Problem assessment of potential impacts	May 1968–June 1969	32 625
University of Illinois	Potential agricultural impacts	Nov. 1969–Oct. 1971	38 665
Colorado State University	Development of plan for San Juan Ecology Project	Jan.–Aug. 1970	48 000
Colorado State University (leader) for San Juan Ecology Project	Impacts of Colorado River Basin Pilot Project and longer-range implications	Sept. 1970–Mar. 1976	1 014 000
University of Colorado, Institute of Arctic and Alpine Research	Development of avalanche forecasting technique	Apr. 1971–May 1976	318 105
University of Wyoming	Potential impact in agriculture	Mar. 1971–June 1973	99 966
South Dakota State University	Determination of potential impact on agriculture, environment, and society	Mar. 1971–June 1973	128 800
North Dakota State University	Determine potential impact on agriculture, environment, and society	Mar. 1971–June 1974	125 000
Montana State University	Determine potential impact on agriculture, environment, and society	May 1971–June 1973	152 900
University of Wyoming for Medicine Bow Ecology Project	Impacts of increased snowpack and nucleating agents in Medicine Bow study area	Sept. 1971–Feb. 1975	206 500
Colorado State University	Determine effect of silver in rumen and cecum digestive systems	Oct. 1971–Aug. 1973	32 089
University of California, San Diego	Assess potential impact of snow augmentation in northern Sierra Nevada	Feb. 1973–Oct. 1974	29 631
Colorado State University	Assess potential impact of summer-convective rainfall enhancement on the High Plains	Dec. 1973–May 1974	74 758
Pacific Southwest Forest and Range Experiment Station, Forest Service	Perform preliminary studies for Sierra Ecology Project	Aug. 1975, continuing	58 000
Utah Division of Water Resources	Impact of additional snow in the Uinta Mountains	Dec. 1975, continuing	160 000
Human Ecology Research Services	Analysis of public response to snowpack augmentation in the Sierra Nevada of California	May–Nov. 1976	7 096

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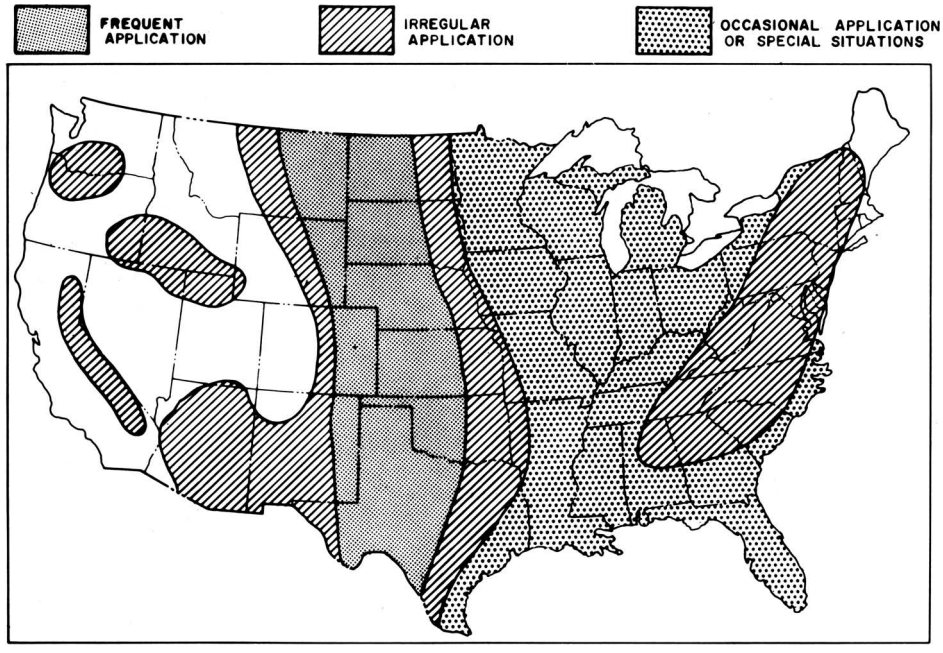

FIG. 1. Areas of most likely application of summer-convective precipitation management.

uses, such as navigation, recreation, dilution of wastes, and sweetening of saline estuaries, will take place only in particular situations where such use is exceptionally valuable.

6) Applications related to rain-fed crops will occur frequently where the drought hazard is most acutely perceived and, perhaps, in other areas where agricultural productivity would benefit even during nondrought periods, especially where agriculture is intensive. They will be infrequent where crops depend primarily on irrigation derived from distant sources or where insufficiency of moisture is an infrequent cause for concern. "Crops" will come to include forest and rangeland areas brought under technological management.
7) Applications will be regulated and managed in response to local or regional needs and to environmental, economic, social, and technological constraints.
8) The amounts of precipitation increase attained by intensive precipitation management will be similar to the capabilities projected on the basis of current experimental results. These projections are discussed in the following sections.

Figure 1 shows where applications of summer-convective precipitation management seem most likely to occur under the conditions assumed. The most extensive use is likely to be for rain-fed agriculture. Use for augmentation of water storage for end uses including irrigation, hydroelectric power, and municipal and industrial supply will occupy restricted areas where watersheds are already developed for these purposes. The figure suggests that occasional applications may be expected over very large parts of the nation, whereas frequent application will probably be confined to much smaller areas.

Figure 2 shows where applications of winter-orographic precipitation management seem likely. Besides the obvious limitation that they will be confined to highland regions of the United States, there is notably greater consistency in the likely frequency of application. Most end uses of the water, whether for irrigation, hydroelectric power, municipal and industrial supply, or groundwater recharge, characteristically take place at a distance from the site of the snowpack augmentation.

a. Impact on weather elements

Current estimates of additional precipitation obtainable by cloud seeding are diverse and controversial. An important aim of Skywater research projects is to improve the basis for those estimates. The estimates incorporated into environmental impact assessments are an attempt to represent what is likely to result from successful development of the technology. If success is not achieved, there will be no widespread application to cause impacts.

1) SUMMER-CONVECTIVE CLOUDS

The opportunity for increasing precipitation from summer-convective clouds appears now to lie chiefly with clouds of moderate size and moderate dynamic instability. Small clouds, even if doubled in rain output, would contribute but little. The larger convective clouds and cloud systems produce precipitation with such regularity that cloud seeding is likely to have but little effect. Therefore, precipitation management is likely to make medium-sized showers more frequent without much affecting the frequency of spatters or downpours.

Stimulation of medium-sized showers may increase the frequency with which they merge and combine to form multishower systems. Such systems tend to produce

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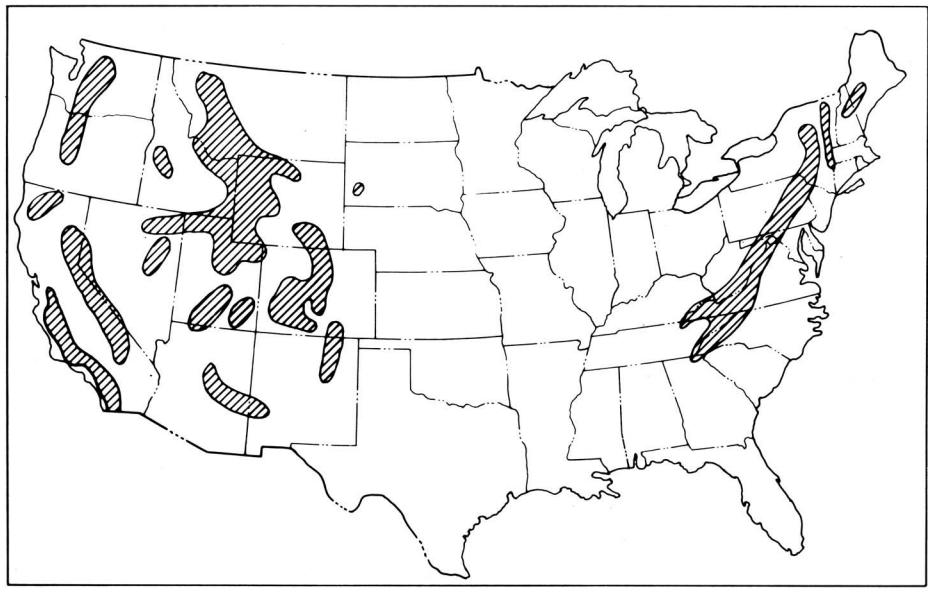

FIG. 2. Areas containing mountain crests suitable for winter-orographic precipitation management applications.

more than isolated shower clouds do. Promotion of mergers in borderline cases may prove effective for rain augmentation. However, since such mergers and transformations occur naturally when the potential for severe weather is high, the likelihood that seeding for precipitation increase would take place in the face of the risk of severe weather and that it would increase the frequency of damaging storms appears slight. There may be an exception when hailstorms are seeded for the joint purpose of rain increase and hail suppression, in which case, however, the hail suppression motive would dominate. There is a broad consensus in the scientific community that the potential of the methods currently under development does not exceed the range of 10–30% increase in the areawide, season-long precipitation. It is appropriate to take the liberal end of this range in assessing the effect that stimulated precipitation might have on other components of the environment.

2) Winter-orographic clouds

There is somewhat better agreement among experts as to increases that may be expected from winter-orographic cloud seeding, and it is generally regarded as closer to the point where the potential of a mature technology can be predicted. It has become evident that site factors loom large. For practical reasons, sites with potentials much <10% increase from seeding are unlikely to become the scene of operations. For the most favored localities, an increase of 30% could be regarded as a generous but not unreasonable expectation from a mature technology intensively applied.

In the experimental situations that have received the most intensive study, storms thought most suitable for stimulation are those with moderate cloud depth and wind strength. These, when seeded, deposit additional snowflakes near the mountain crests. Storms with very deep cloud systems and strong winds apparently already supply enough, perhaps too many, ice nuclei for precipitation, and any added snow crystals formed by seeding blow beyond the mountains and reevaporate. In some cases, however, no reliable relationship between the severity of a storm and its susceptibility to seeding has been found. Considering the constraints likely to be imposed on the seeding of severe storms, it is likely that the frequency of moderate snowfalls will be increased much more than the frequency of severe ones. Tentatively, the same conclusion may be stated with respect to storm duration.

3) Effect on precipitation in nearby areas

It is surprising how many people, including those who commented on the draft version of the Skywater environmental statement, appear to assume as inevitable that augmentation of precipitation in one place must cause its diminution somewhere else. Most often cited in support of this plausible but fallacious assumption is the notion that the extraction of moisture by augmented precipitation dries out the atmosphere and, thus, leaves it less capable of producing subsequent precipitation. The fallacy lies in failure to appreciate 1) the role of natural atmospheric disturbances in causing the convergence and ascent of moist air as the dominant mechanism that makes moisture available for cloud formation and 2) the potential of cloud seeding both for increasing the dynamic energy of such disturbances and for increasing the efficiency with which the storm clouds are converted to precipitation (storm clouds that would naturally "blow out" a greater proportion of their moisture to the stratosphere). Model studies of convective rain clouds are not far enough advanced to predict the outcomes with high confidence, but at least they

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offer no encouragement to the notion that cloud seeding robs Peter to pay Paul.

Studies of rainfall downwind from actual summer-convective cloud seeding operations have been inconclusive, with the evidence tending to favor some increase out to distances of 400 km or so. However, the types of operations involved have been so disparate that no general conclusions are possible. Studies of precipitation downwind of winter-orographic cloud-seeding operations confirm the presence of increases at distances of ~250 km. The evidence, therefore, does not support the notion that stimulation of precipitation in one area deprives another area but suggests that seeding may strengthen existing precipitation systems.

A less direct effect of winter-orographic snowpack augmentation on rainfall may come about if the additional water is used to extend irrigation into areas where it is not now practiced. It has been shown (Changnon, 1974) that evapotranspiration from large irrigated tracts is associated with an increase in showery precipitation over neighboring areas. Such an effect, if it were felt, would most likely affect arid to semiarid range and scrubland and high-altitude forests adjacent to the newly opened irrigation districts.

The western Great Plains area is subject to frequent periods of hot, dry air that sometimes causes severe crop damage. Successful augmentation of local summer-convective rainfall will cause local increases in humidity close to the ground that will last until the added water is evapotranspired or percolates to deeper soil horizons, or until a later rainfall event erases the effects of the earlier one. Whether or not the resulting decrease in the frequency of periods of hot, dry air will result in less crop damage cannot be determined at this time.

4) Amount of sunshine

Precipitation management is not likely to have a discernible effect on the amount of sunshine. Patterns of sunshine and cloudiness are governed by large-scale weather patterns not subject to the effects of cloud seeding. Even successful promotion of cloud mergers, affecting only a small subset of cloud formations, would not palpably affect the duration of sunshine.

5) Global-scale effect on hydrologic cycle

Grounds for postulating a global-scale effect of widespread precipitation management on the hydrologic cycle are extremely speculative. Even internationally widespread precipitation management would probably involve quantities of water substantially less than those already involved in the practice of irrigation, and much less also than the average annual variability of natural precipitation on a hemispheric scale. Even where seeding agents have been dispersed for hail suppression in quantities much larger than those used for precipitation management, there has been no evidence of effect on the weather that could be attributed to persistence longer than a day or two. Though the possibility of a global-scale environmental effect of widespread precipitation management cannot be entirely ruled out at the present time, the likelihood of any significant effect is considered extremely remote. The verification of such an effect, in the face of other natural and man-caused variables, would be very difficult.

b. Impact on human activities

1) Agriculture

Of all applications of precipitation management, the most frequent and extensive are in connection with agriculture and, in particular, with alleviation of drought in subhumid and semiarid regions. Under the assumptions stated earlier in this section, agriculture in these regions will continue to be the focus of application. How might this change the general character of agricultural practice? In particular, might it produce a dependency on the continued success of precipitation management that, if the latter were to fail, could cause a catastrophe?

Agriculture in the United States has been continually in a state of adjustment to emerging ideas, usually spurred by stark necessity. The Great Plains have seen, in succession, a catastrophic degree of overgrazing of "public" lands; expansion, collapse, and readjustment of dry farming; the extension of irrigation followed by the sale of irrigation water rights for municipal and industrial use; and lately the substitution of stubble-mulch tillage for deep plowing and intensive farming of selected soils combined with abandonment of others (Auclair, 1976). One can postulate, with a certain degree of rationality, how agriculture might tend to adjust to any real change in rainfall climate achieved by precipitation management. Whether this adjustment will be as postulated, or will be actually discernible and subject to separate management in the face of much larger adjustments to political, economic, technological, and social changes, is open to question. Perhaps most questionable is the assumption that significant adjustment might take place in anticipation of an effective role for precipitation management.

Demonstrated long-range success of precipitation management would bring about an adjustment of land values between the precipitation-managed regions and other lands producing the same or substitutable crops. In the past, such adjustments have taken place in the case of irrigated land. Adjustments due to precipitation management would probably be of lesser magnitude than those due to irrigation but subject to similar political and economic controls.

2) Hydroelectric power

This is probably second in prominence on the list of applications for precipitation management. The motivation has usually been the increased economic return from existing investments in installed generating capacity through more intensive utilization, especially when the resulting extra power can be sold at peak rates during the hours of highest demand. Once precipitation management becomes an accepted technology, it is likely that the opportunity for increased return on the large capital investment involved in hydroelectric de-

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velopment (or assigned to the hydroelectric compartment of multiple-use water projects) will tend to lend additional justification to marginal hydroelectric projects, including pumped-storage projects where there is an opportunity to supplement the pumped supply with streamflow augmented by precipitation management. It does not appear likely, however, that precipitation management will be more than a subsidiary factor in the economic considerations involved.

3) Municipal and industrial water supply

Substantially increased demands for water for this purpose are projected in certain areas of limited supply. It is unlikely that precipitation management will displace other responses such as water conservation and reuse. It is likely, however, that a mix of strategies will emerge that includes precipitation management in the role of a low-cost but limited capability alternative utilized to a limited extent.

A principal component analysis of agricultural and economic characteristics of six counties arrayed across the precipitation gradient from Colorado to Illinois (Howell, 1976) showed strong precipitation-related differences among them. Cluster analysis showed that the wetter counties had a high proportion of land in harvested crops, large investments in farm equipment, and a dense population, while dry counties had much idle (fallow) cropland and produced hay and cattle. Between the extremes, there was a set of counties characterized by a mixture of dry farming and irrigation, where fallow cropland and production of small grains were prominent. The analyses suggest that precipitation management would tend to shift these existing patterns of land use and related human activities slightly westward without much affecting the character of the patterns themselves.

4) Summary

Human activities in the fields of agricultural, hydroelectric, and municipal-industrial use of water are likely to undergo adjustment to precipitation management through a mixed-strategy approach that will not place an inordinate degree of dependency on the continued ability of precipitation management to meet performance targets.

c. Impact on the natural environment—Summer convective

Over most of the civilized world, the natural environment is profoundly acculturated and bears few traits of wilderness. In considering the natural environment, one must, therefore, regard the environment as it is exemplified by the real landscape. Except for a few pockets of wilderness, the environment is the product of an ongoing symbiosis between the land and humankind (Dubos, 1976). It is, nevertheless, useful to make the distinction between the direct, intentional impact of precipitation management on a cultural element such as agriculture and the complex of indirect effects that may impinge on other elements of the landscape and biosphere, be these "natural" or cultivated.

If precipitation management is applied to agricultural cropland in subhumid and semiarid regions, the largest receptor of indirect effects will be the surrounding and interspersed grasslands, scrublands, and breaks. The western Great Plains, from Montana to Wisconsin, from Colorado to Illinois, and from New Mexico to Mississippi, are remarkable in displaying an environmental continuum across a gradient of precipitation that increases ~10% with each eastward displacement of 60 km. This landscape is, therefore, a permanent exhibit of the potential eventual influence of widespread and prolonged precipitation management on the environment.

1) Runoff and groundwater

The abiotic characteristics of the environment, such as runoff, groundwater, erosion, and soils, are greatly influenced by physiography as well as precipitation. Runoff, which is intermittent at the dry end of the gradient, increases gradually with increasing summer-convective rainfall (in absolute quantity per unit area and as a proportion of the precipitation), and the coefficient of variation decreases. Groundwater recharge also tends to increase, but effects are overwhelmed by those of physiography and underlying geology.

2) Erosion

Erosion has been found to be greatest ($\sim 28\ g\ m^{-2}\ yr^{-1}$) where the rainfall is $\sim 270\ mm\ yr^{-1}$ (Langbein and Schumm, 1958). In regions of lighter rainfall, the amount of erosion is dependent upon the amount of energy expended on the soil by falling rain and running water. Where the precipitation is greater, vegetation that tends to bind and protect the soil and susceptibility of particular soils to erosion are the dominant factors. About 83% of the variation in eroded soil has been attributed to vegetative cover in combination with litter, slope, and soil organic content (Meeuwig, 1970). In regimes of heavy rainfall, erosion is usually evident only where vegetation is disturbed. Since, under the assumptions previously stated, it is unlikely for economic and practical reasons that precipitation management will be applied in regions of <270 mm annual precipitation, its effect will be to decrease erosion except in regions of disturbance. Since agriculture represents by far the most widespread disturbance, the actual effect of precipitation management will be determined principally by the efficacy of control measures practiced in connection with agricultural land use, and the effect of precipitation management will be quite secondary.

3) Soil types

These are recognized as the end product of accommodation among geological, vegetational, animal, and climatic factors. Within the Great Plains, two or three diffuse boundaries between soil types may be found that are to some degree related to summer-convective rainfall amounts. Precipitation management would presumably cause an eventual slight shift in the position of these diffuse boundaries over a very long period of time.

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4) Vegetation

With respect to the vegetational characteristics of the environment, increasing summer-convective precipitation is accompanied by a gradual transition from desert shrubland, to short-grass prairie, to tall-grass prairie, to a sabana of mixed grass and deciduous forest, and finally to forest. This transition has, of course, been drastically modified by cultivation and land use, by irrigated cropland and grazing in the drier part, and by dryland crops and row crops in the progressively moister parts. Precipitation management would tend to shift the very diffuse boundaries of these grand divisions somewhat westward.

Each vegetational province is characterized by a spectrum of plant species, including many specimens of species adaptable to both wetter and drier climates and warmer and colder climates. With the normal short- and middle-term variations in climate, both relative and absolute abundance of different species often vary greatly from one epoch to another, but the absolute range of most species is little affected. Thus, it was found that during the drought of the 1930s the more moist-adapted species were suppressed over wide areas but did not disappear. When the drought ended, the dry-adapted species, which had suffered less, at first grew exuberantly but were later crowded down and suppressed (but not extinguished) by recovery of the moist-adapted species. Precipitation management, to the extent that it may moderate the intensity of extreme droughts, will cause the natural vegetation of each locality gradually to resemble that of regions now slightly moister and may moderate the secular changes in species composition that take place in response to normal climatic fluctuations.

Respecting vegetation, it should be noted that acculturation has profoundly modified species composition and may continue to do so. Overgrazing of the High Plains in the late 19th century resulted in drastic and apparently permanent change in the species composition of the grassland communities, with disappearance of the forage species preferred by the cattle and, in many places, displacement of grasses by desert shrubs and forbs. In some moister locations, the original species structure has been supplanted or greatly modified by the introduction of improved pasture grasses. It is highly probable that such cultural practices will continue to exert much greater influence upon the character of vegetational communities than will precipitation management and will probably entirely mask the latter.

5) Animal populations

The effect of precipitation management on animal populations is likely to be mainly indirect, through its influence on habitat, rather than directly on the organisms. Particularly in the case of birds and small mammals, populations depend more on the presence of suitable cover, nest sites, and food supplies than on the weather. Though severe storms at critical times may occasionally decimate some species, there is little expectation that precipitation management would affect the frequency of such occurrences.

Although it has been proposed that outbreaks of disease, weeds, and insect pests are facilitated by any major ecosystem disturbance, the interaction between the environment and precipitation management will effect only gradual change and adjustment. It will not cause disturbances like those of acculturation or like a multitude of natural acute disturbances such as fire and drought. In fact, to the extent that precipitation management reduces the intensity of drought, an important source of ecosystem stress will be diminished.

6) Summary

The best expectation presently available of the impact of summer-convective precipitation management is that each present environmental compartment would gradually come to resemble neighboring compartments on the moister side of the precipitation gradient, with no apparent risk of severe disturbances accompanying this transition.

d. Impact on the natural environment—Winter orographic

The setting for winter-orographic precipitation management, comprised mostly within the more remote parts of mountain ranges, is affected less by acculturation than are other regions. Nevertheless, such activities as lumbering, mining, livestock grazing, game management, recreational development, and fire protection have already greatly modified the aboriginal environment and continue to do so.

By virtue of the environmental impact studies begun in the early 1970s in connection with Skywater winter-orographic experiments and recently reported upon, the relationship of snowpack augmentation to certain processes considered to be most significant environmentally has been established or at least estimated.

1) Snow cover extent and duration

The most important impact of precipitation management, through which other environmental compartments are affected, is on the extent and duration of snow cover as it retreats in the spring. The snow cover release date establishes the beginning of soil warming and of the growing season for most vegetation and may affect the duration of adequate moisture supply for growth. From Forest Service studies, it appears that a snowpack 150% of normal delays the disappearance of snow cover at a given location by ~5 days, leading to an estimate of 1–3 days' delay resulting from precipitation management. This estimate is probably too high for windswept areas and too low for the much smaller areas where snowdrifts accumulate.

2) Avalanche hazard

The relation between snowpack augmentation and avalanche hazard is greatly complicated by other factors affecting the release of avalanches and affecting the prediction, warning, and application of countermeasures that mitigate this hazard. In chutes where they seldom

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run, avalanches occur under rare conditions of recognizably high avalanche danger, when cloud seeding would be suspended under accepted procedures. In areas of high avalanche frequency, such as many chutes in the Red Mountain Pass area of the San Juan Mountains, many avalanches run during nearly every major storm, and successful forecast and warning procedures have been developed, at least partially under the spur of prospective precipitation management. The occurrence of delayed avalanches, after the storm has passed, is related partly to the augmented part of the snow load and mostly to features of snow stratigraphy and metamorphosis not affected by precipitation management. To the extent that precipitation management focuses attention on avalanche warnings and countermeasures, it will tend to reduce, not increase, the hazard.

3) Geomorphic processes

In its effect on geomorphic processes of soil erosion, mudflow activity, and transport of dissolved solutes, snowpack works through processes at a secondary level, through indirect links with vegetation and small mammals. Soil erosion occurs mostly in summer and where vegetative protection is lacking, and it tends to be greater at the margins of late-lying snowbanks where vegetation is sparse. Thus, an increase in the extent of late-lying snowbanks would likely have a discernible but highly localized effect on soil erosion. In the San Juan Mountains it was concluded that "other forms of man-induced erosion usually overwhelm the natural variability since they involve increases of orders of magnitude rather than a few tens of percent" (Caine, 1976).

4) Stream runoff

Snowpack augmentation affects stream runoff and related characteristics mostly in the headwaters portion of watercourses where regulation is usually absent. Simulation of particular sites under study has shown that precipitation management there would have no identifiable effect on the frequency and magnitude of flood flows.

5) Alpine vegetation

The impact of snowpack augmentation on alpine vegetation has been investigated mostly by installing snow fences to increase local snow accumulation in a gross manner and then observing the subsequent vegetational changes. In the San Juan Mountains, Webber *et al.* (1976) found that a 1-week delay in snowmelt would occasion only a small reduction in biomass productivity, becoming serious for a 4- to 5-week delay. They concluded that a 15–30% snowpack increase over several decades would cause both qualitative and quantitative changes in vegetation, minor in nature and affecting probably <10% of the alpine area, and that the incidence of rare species might increase as a result. "These conclusions," they said, "refute the popular notion that tundra is a fragile ecosystem."

On the San Juan Ecology Project, several study plots were located in subalpine forests and adjacent grassy parks. The distribution of tree species was found to be strongly related to snowmelt date, which, in turn, depended greatly on elevation and exposure, southern slopes in the forest zone often becoming snowfree betweeen storms during the winter. Spruce growth was independent of snowpack depth, the amount of growth being apparently genetically controlled, whereas aspen was more responsive to spring soil temperature. Seasonal growth of ponderosa pine was positively correlated with the precipitation of the previous December.

Stable aspen stands give way to fir, then spruce, as one goes to sites with longer snow duration and lower temperatures (Dix and Richardson, 1976). The seedling stage is the most sensitive to increased snow duration, and the maximum density of seedlings would tend to shift to sites that now have earlier snowfree dates.

Variations in wood production directly attributable to delay of snowfree date were not detected. In spruce and fir, wood production was found to be constant.

Among the herbaceous plants, the timing of the earliest phases of seasonal development was found to vary directly with the snowfree date, but this dependency became less and less marked as the season progressed, and all species completed their development within the growing season. Although precipitation management might delay the phenological coming of spring, especially in pockets of snow accumulation, it was considered unlikely to have a direct effect on herbaceous populations except perhaps to reduce biomass production somewhat.

In oak brush, which in parts of the San Juan Mountains is an important browse for elk, production was found most closely related to the amount of the previous summer's precipitation and to be very little affected by snowpack.

In the Medicine Bow Mountains, decomposition of litter was found to be unaffected by increased snowpack. Leaching of nutrients from the soil did not appear to be large, but adequate determination of it was not achieved because of premature termination of the study due to funding cuts (Knight, 1975).

6) Animal populations

The relationship between snowpack augmentation and the winter range of elk was studied in the San Juan Mountains (Sweeney and Steinhoff, 1976). About 28% of the relevant elk winter range, as mapped by the Colorado Division of Wildlife, fell within the study area of the Skywater cloud seeding experiment, all of that range being within the portion of the study area designated as upwind flank. It was found that a hoof penetrable snow depth of 40 cm initiated downslope migration, whereas a penetrable depth of 70 cm or more was avoided. In a model of winter range in the Missionary Ridge area, a 15% snowpack increase was found to correspond to a decrease in this part of the winter range varying from 0 to 20% depending largely upon antecedent snow conditions. Springtime upslope movement was regulated by the greening of vegetation rather than by retreat of snow line, and in each season there appeared to be ample habitat available for calving. The

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study suggests that impact on large animals should be assessed on a project-by-project basis with attention given to the probable distribution of snowpack increase between the winter range and the higher elevation parts of the target. Recent studies suggest that most and perhaps all of the snowpack increase available in the San Juan Mountains will be at the higher elevations, above the winter range.

Studies of the effect of snowpack on small mammals were made in the alpine zone (Stoecker, 1976) and at several forest zone sites (Sleeper *et al.*, 1976). In the alpine zone, the pocket gopher is the animal of principal importance, since the amount of earth it moves is significant for local vegetation and for geomorphic processes. There is some suggestion that snow cover may restrict the gopher winter home-range size, but no clear effect on distribution or activity was found.

At the most intensively studied forest site, there was a marked decline in population density of chipmunks and deer mice after heavy-snowpack winters with full recovery of the chipmunks and partial recovery of the deer mice during the following summer. At other sites, however, either no effect or even a weak positive relationship between deer mice and snowpack was found, so the effects are believed to vary from site to site and may depend upon differences in site dryness. No effects on voles were found.

7) Subalpine lake

In the Medicine Bow Mountains, effect of increased spring runoff on a subalpine lake was studied (Parker and Condit, 1975). It was concluded that increased runoff would tend to decrease the standing crop of phytoplankton, the amount of the decrease depending on a variety of factors such as wind, spring air temperature, etc., not influenced by snowpack augmentation. The opinion was expressed that the lake would not suffer any perturbation as a result of snowpack augmentation that would not occur in its absence.

8) Trout production

This was also studied in the Medicine Bow Mountains (Baxter and Loar, 1975). Though a drastic snowpack increase would probably decrease trout production, it appears that moderate increase would have no appreciable effect. Production of trout and the benthic invertebrates upon which they feed is apparently influenced as much by variations in the pattern of runoff and by late summer air temperature as it is by the volume of snowpack.

9) Summary

In their syntheses and discussion of the San Juan Ecology Project, the investigators concluded as follows (Caine *et al.*, 1976, pp. 12–13):

> The results of the San Juan Ecology Project suggest that there should be no immediate, large-scale impacts on the terrestrial ecosystems of these mountains following an addition of up to 30 percent of the normal snowpack, but with no addition to maximum snowpacks. Further, much of the work reported here suggests that compensating mechanisms within the studied ecosystems are such that any impacts would be buffered, at least for short periods of time, and of lesser magnitude than the changes in snow conditions required to produce them.
>
> However, some parts of the mountain ecosystem are much more susceptible to changes in snow conditions than others, so important local effects are possible. In general, these susceptible components are very small parts of the entire system but their economic or esthetic value may be much greater than their mass or area suggest. Remedial action is possible in most of these cases but has not been studied in this project. Our work has shown three ecosystem components to be most susceptible to increased snowfall: (1) snowbank situations at elevations above treeline; (2) elk herds (in other mountain ranges other big game species may be similarly affected); and (3) some small mammal populations, especially the deer mouse. Not all of these impacts are necessarily deleterious; an increase in the area of snowbank edge habitats in alpine area may, for example, increase the niches available for rare plant species.
>
> Finally, even in the small areas where we predict greatest impacts from increased snowfall, the changes involved are unlikely to approach the magnitude of other man-made impacts on mountain ecosystems. However, it should be remembered that they may act in phase with other man-made impacts and with natural climatic changes, in which case the total effect could be much greater than our studies suggest.

e. Impact on the natural environment—Seeding agents

Of the various seeding agents, silver iodide is the only one perceived as having potential environmental impact. This perception comes mostly from the strong bacteriocidal action of some forms of silver. Following the recommendations of Cooper and Jolly (1969), Skywater investigations of potential silver impacts were directed at microbial and aquatic compartments (since these were the most important and most accessible to study) as well as at monitoring the silver in cloud-seeding study areas.

Figure 3 summarizes in a tentative, generalized way the silver content of the principal environmental compartments in the contiguous United States, the concentration of silver in each compartment, and the rates of exchange between them, based on interpretations of current literature. The soil compartment (including also mud and vegetable litter), calculated for the top 20 cm comprising the root zone, contains by far the largest quantity of silver, at concentrations that may become quite high in mineralized areas. Living matter of all sorts from microbes and fungi to animals (shown as "Living" in Fig. 3), which has on the average a slight tendency to concentrate silver from the soil, contains the next largest quantity. The exchange between living matter and soil through uptake and decomposition (designated by the diamonds related to the bottom scale) dominates all other exchanges by at least an order of magnitude. The rates of exchange are slow enough so that the contents of these two compartments must change only slowly.

The silver concentration and content in lakes and rivers (shown in Fig. 3 as "Water") are determined mainly by depositional and erosional exchanges with the soil and by runoff to the sea, whereas uptake and decomposition exchanges with plants play a lesser role.

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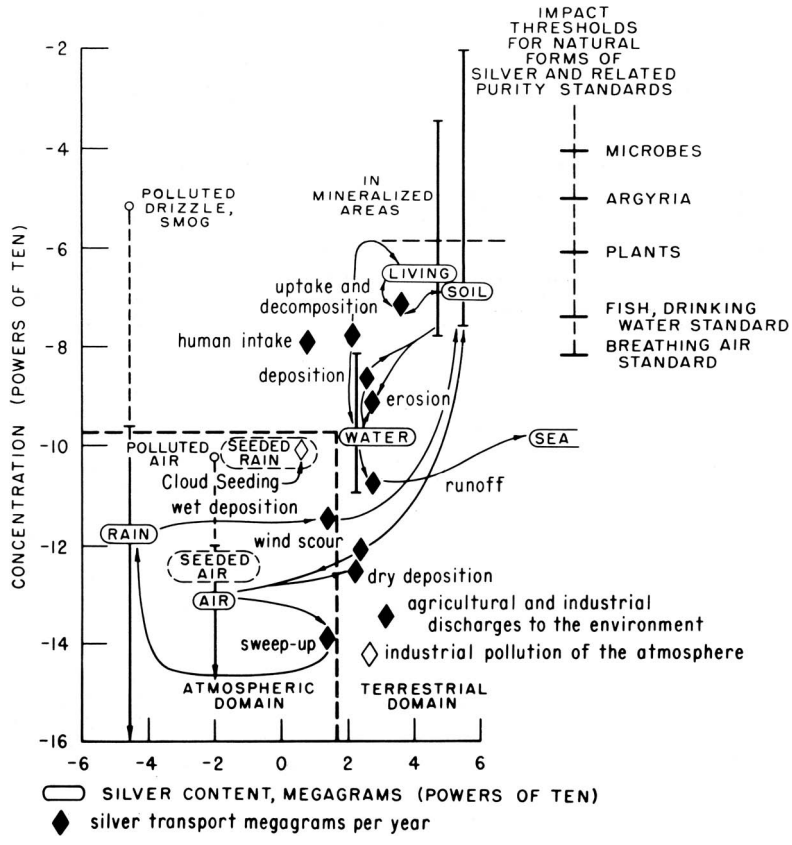

FIG. 3. Generalized approximate content and concentration of silver in environmental compartments for the contiguous United States, rates of exchange between compartments, and impact threshold concentrations. Representations of exchange rates relate only to the scale of megagrams per year (bottom scale), not to scale of concentrations.

In the aquatic compartment, annual transports are of the same order of magnitude as contents. Most transport is thought to be by waterborne sediment.

The atmospheric domain receives silver in the form of windblown dust, some of which returns to the soil as dry deposition and some of which is swept up by particles of precipitation (the label "Rain" includes snow) and is carried with it to the ground, to lakes, or to the sea. The silver content of the atmospheric compartment at any moment is small in comparison with the annual transport through it.

Silver transports associated with cloud seeding and with pollution are shown in Fig. 3 by open diamonds. Atmospheric pollution causes local, temporary changes within the atmospheric compartment that are very large in comparison with natural amounts. Industrial atmospheric emissions are variously estimated at 135 to >360 Mg (150–400 tons) per year (Carson and Smith, 1975; Environmental Protection Agency, 1973), at concentrations ranging from $\backsim 10^{-10}$ in city air to an extreme of 6×10^{-6} measured in the smog water within the downwind plume from a copper smelter (J. Fletcher, 1976, personal communication). The other main source of silver pollution affecting the soil and surface waters is fertilizer, either Florida phosphates or processed sewage sludge (Carson and Smith, 1975). Qualities and concentrations so produced are currently unknown.

Cloud seeding, if it became widespread, would result in local, temporary concentrations in precipitation of the same order of magnitude as the natural concentration in surface waters. However, the rates of exchange would remain more than an order of magnitude smaller than the principal exchanges affecting the aquatic compartment, and they would be many orders of magnitude smaller than those affecting plants and soil, even in localized areas of precipitation management. Widespread and prolonged precipitation management, using silver iodide as the cloud-seeding agent and assuming that all the silver dispersed in the course of a century accumulated in the top 2 cm of soil, would not cause the silver concentration there to exceed the normal background. Silver from seeded rain follows pathways essentially identical to those from natural rain, and the effect of it on the silver transport by wet deposition (an increase of <20%) is too small to be illustrated conveniently in Fig. 3.

The threshold of silver concentration for observable impacts on microbes and pollens in the laboratory broadly overlaps concentrations in naturally enriched regions and probably in sites of highest industrial pollution and some areas of fertilizer use. Precipitation management activities produce such concentrations only within a few meters of ground-based smoke generators, where some weak evidence of possible delay in de-

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composition processes is available (Sokol and Klein, 1975). Elsewhere, despite diligent monitoring, no trace of silver attributable to cloud seeding, or impact of such silver, has been found.

It has been hypothesized that addition of silver to near impact threshold concentrations might retard decomposition and allow a higher accumulation of organic matter in the soil. Whether such accumulation actually occurs, or whether it would be harmful if it did occur, has not been determined. The possible emergence of silver tolerant microbiotic ecotypes in naturally or artificially enriched areas has not been investigated. At any rate, evidence of gross inhibition of decomposition in naturally enriched soils under field conditions is lacking. The time scale of accumulation and migration of silver from soil to plant tissues and back appears to be such that assimilation of imposed silver iodide or other silver-bearing pollutants to the naturally prevailing forms of this element would be rapid in relation to the accumulation itself and would determine the forms of silver actually present and active in the soil. Only the amount of silver dosage, not its initial chemical form, would be significant.

3. Human responses to the environmental impacts of precipitation management

The scope of the environmental movement has not stopped at the limits of the natural environment but has come to embrace impacts upon mankind. In the environmental sense, the focus of concern is not upon the principal actors—the cloud seeders and their clients—but upon persons and institutions indirectly affected and upon bystanders. Sociologists and political scientists have evinced also a lively interest in understanding the behavior of persons who support or oppose precipitation management at all levels, from local to national.

1) Social institutions

With minor exceptions, precipitation management is not seen as altering the structure or functions of societal institutions, since these are already well adapted to dealing with new services. Attention has been directed mostly to considering how existing institutions will interact with precipitation management and what shape they will give it.

2) Regulatory measures

The most characteristic response to potential adverse impacts takes the form of regulatory measures aimed at mitigating them. Since precipitation stimulation during a flood would be disadvantageous, as indeed would be any action tending to aggravate a climatic extreme, such actions are prohibited in all jurisdictions that regulate weather modification operations. In practice, these prohibitions extend to a number of environmental hazards including avalanches, hail, severe local storms, floods, adverse effects on crops or agricultural fieldwork, and even interference with the county fair.

3) Adaptation to undesirable effects

Another response is adaptation to a possible undesirable effect such as an increase in plant diseases. Since precipitation management is not known to present any hazards not already the concomitants of natural weather occurrences, adaptive strategies (e.g., spraying to control mites) are already developed to varying degrees. Experience to date suggests that widespread and prolonged application of weather modification will be accompanied by an insistence on further study of potential undesirable effects and means of coping with them, but future specific responses outside the existing pattern are not now identifiable. For example, a review by the California Department of Highways of probable responses to snowpack augmentation indicated that no change in current practices respecting snow clearance and associated safety activities is anticipated.

In instances where weather modification for the benefit of one interest imposes an identifiable undesirable effect on another interest, compensation has been proposed and discussed in principle (e.g., Taubenfeld, 1968), but the manner in which degrees of causality and liability might be established in practice remains to be determined. The most likely arena for the development of this response is that of agriculture, where adjacent crops may benefit from moisture, or dryness, at differing stages of their development.

4) Collateral benefits

Responses to collateral benefits from environmental impacts are also likely to follow strategies already established for dealing with the vagaries of the weather, and only the degree and frequency of such responses rather than their nature are likely to change. For example, if rain stimulation for the benefit of wheat lands were to increase the carrying capacity of nearby wildlife ranges, the number of hunting licenses issued annually might change, but the general strategy of game management would remain unaltered. Similar responses to collateral benefits are to be expected throughout the network of water uses.

5) Summary

The only novelties likely to be manifested as a result of widespread and prolonged weather modification are extension of related environmental research and development of principles for the compensation of interests negatively affected by actions undertaken in the name of the general welfare.

4. Environmental impact of Skywater activities

More than 15 programs of field experimentation involving cloud seeding have been carried out since 1965 under Skywater sponsorship, ranging from brief expedition type efforts to 4- and 5-year pilot projects in Colorado and North Dakota. Further experimentation is scheduled in the High Plains area and in the central Sierra Nevada. Current policy has required that the immediate impacts of these activities, as well as the impli-

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cations of widespread and prolonged applications that might crown their success, be assessed.

The pattern of results has given strongly significant indications of effects on certain definite categories of clouds combined with mostly weak and insignificant effects averaged over the area and duration of the experiments. Exceptions are results of the North Dakota Pilot Project, which showed significant areawide increases of the order of 12% (Dennis *et al.*, 1974) and possibly shorter programs of hygoscopic seeding in Texas and Oklahoma (Bureau of Reclamation, 1976b). Thus, the actual environmental impacts of Skywater activities have to do mostly with certain individual storm events for which a high probability of effect may be presumed. Unfortunately, the means are not at hand for measuring or even estimating the magnitude of these effects because of their extremely large variability under natural conditions. For this reason, all environmental impacts of Skywater activities are subliminal and defy identification. The most that can be said is that they are too weak to be manifest.

Impacts too weak to be manifest may nevertheless be real and may even be environmentally and economically important. Estimates of the magnitude of such subliminal impacts have been made by inference from studies of the environmental effects of natural precipitation variations. For example, it has been estimated from crop data that each added centimeter of summer rainfall in western North Dakota increases the biomass production of rangeland by $\sim$60 kg ha^{-1} (Johnson, 1974). On this basis, one may estimate that the North Dakota Pilot Project caused some supposed increase in rangeland biomass production, even though this impact is not directly verifiable by observation. Such methods of estimation, questionable as they are, provide the only presently available means of assessing impacts of the Skywater experiments or of taking such impacts into account in decision making. None of the impacts so far assessed in this manner are strong enough or certain enough to warrant further consideration.

5. Current and future progress and problems in evaluating impacts

a. Research approach

Nearly all of the environmental research so far undertaken in the name of weather modification has responded to particular potential hazards affecting identifiable interest groups (such as the carrying capacity of winter game ranges) or to specific environmental characteristics seen as particularly important (such as the range of principal forest species). This orientation was reinforced by the assessments by a working group of the Ecological Society of America (Livingstone *et al.*, 1966, p. 43) that prolonged application of precipitation management on even the mesoscale would produce "shifts of range, local or complete extermination of species, and at least an initial increase in weeds and pests." As indicated by Steinhoff and Ives (1976), the research approach was mostly aimed at understanding the physical processes relating these particular potential impacts to increased precipitation, focused on the particular impacts that it was thought might be most important.

b. Observational approach

As the work progressed, the methods used became increasingly those of observing instances of gross alterations in precipitation and other interacting environmental factors. For example, in the alpine zone, snow fences were erected that imposed snow loads and durations on the local vegetation equivalent to several hundred per cent increase in precipitation. In the forest zone, the range of study plots embraced a range of climatic conditions larger by orders of magnitude than the anticipated effect of precipitation management.

This method of assessment implicitly assumes that the response of the biological system is linear with the strength of the stimulus. K. Harper (personal communication, 1976) has proposed that, on the other hand, the response is probably nonlinear (increasing as a higher power of the stimulus) on the grounds that most organisms are provided with genetic means of coping with environmental variations within a limited range and become severely stressed only when this range is exceeded. If his view is correct, linear interpolation from observed gross effects of snow accumulation changes will overestimate the true effects. Since the reason for exaggerating the stimulus in the first place is to bring the response up to the level of observability, it may prove very difficult to verify the linearity, or nonlinearity, of the response to the much weaker stimuli likely to result from precipitation management.

There is a temptation to conclude that a response too weak to be significantly observed must be unimportant and to proceed with an action that involves a real but subliminal risk of environmental damage, or subliminal opportunity for environmental benefit. However, human behavior is full of instances of risk-avoidance actions in which the motivation is an image in the mind of the possible adverse consequences rather than a physically or statistically verifiable reality; in other words, a model. A model of the stimulus-response relationship, if credible, becomes the basis for decision making (behavior) even when it cannot be objectively verified at the response level actually involved.

c. Process approach

This method is potentially promising for investigation of relatively strong, direct effects of weather modification on particular parts of the environment. In its present state of development, however, it is incapable of comprehending or predicting the impacts of weather modification on an ecosystem as a whole because the interactions among components are so complex as to defy analysis and simulation. It has come to be recognized that, in the settings so far investigated, the potential disturbing effect of weather modification is overwhelmed by other disturbances to the status quo, some man made and some natural.

From this state of affairs, two broad conclusions are now being drawn. First, since investigation of the points of specific environmental impact thought to have the

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highest potential for effect from weather modification has indicated no clearly adverse effects, emphasis on hurry-up studies to ward off imagined catastrophes, such as species extinctions, no longer appears justified. Second, assessment of long-term effects of weather modification on the environment as a whole is assuming relatively greater importance, and means for such assessment are under review.

For this assessment, the process approach encounters severe difficulties. How the fragmentary and mostly tentative results of impacts on specific environmental components should be formed into an overview of effects on the environment as a whole depends on assumptions about the strength and direction of intercomponent effects. Not enough is know about these effects for more than a speculative exploration. As Cooper (1973, p. 102) noted,

> . . . ecosystems do not necessarily respond in ways that would be predicted from a knowledge of the properties of their individual components. . . . The complexity and variability, in both space and time, of real ecosystems is such that it is probably impossible to devise a generally agreed upon quantitative description against which future states of the system can be judged.

d. Holistic approach

An alternative approach is the holistic, integrative examination of the general properties of environments as a whole after they have developed under the influence of weather differences similar to those expected to result from weather modification. The Special Commission on Weather Modification of the National Science Foundation (1966, p. 20) pointed out that among the avenues open to improved forecasting of biological effects is "examination of areas biologically and climatically analogous to the changed and unchanged situations."

Howell (1976) has shown that short-term and middle-term effects (up to 10 years or so) may be analyzed by observation of environmental system responses to natural trends in the weather elements subject to modification, since natural variations over time spans of 2–10 years exceeding those attainable by weather modification are frequent. A few such studies have been made, especially respecting the recovery of vegetation from the strain of severe drought, but the opportunity appears great for more systematic and widespread application of the method.

e. Comparison of environmental communities

For longer-term effects, especially those spanning the natural successional changes leading to a climax vegetational community, the preferred approach is by comparison of environmental communities that differ in the properties expected to be affected by weather modification but that are otherwise as similar as possible. A well-known example is the vegetational gradient of the Great Plains. Another example, currently under study in the Uinta National Forest, is comparison of vegetation in the interior of a forest stand with that a few tens of meters inside the stand border, where snow blown from a nearby meadow accumulates in late-lying drifts while soil, aspect, temperature, and other conditions are substantially identical. The same general approach characterizes the phytosociological studies of the San Juan Ecology Project (Dix *et al.*, 1973), which established gradients across many stands under different conditions of climate, elevation, and aspect, wherein the principal component of the variations was found to be strongly related to snow duration. This, in turn, was found strongly related to slope aspect. By studying nearly adjacent plant communities under natural conditions that simulate the changes expected from precipitation management, potential impacts may be assessed.

f. Study of natural and acculturated components

Consideration of the wide variety of landscapes that may be subjected to precipitation management suggests that they exemplify "wild" and "cultivated" components that are combined in dramatically varying proportions and modes. In every wilderness area, there is some degree of acculturation, game management being an example. Even in the city, there are some wild pockets. Changes within the wild compartments are for the most part genetically controlled. They include the entire repertory of responsive strategies that have accounted for the evolution and persistence of species and, by and large, render the prevailing ecosystems extremely robust, resilient, and durable under a wide range of stresses and insults, natural and man made.

The acculturated components, on the other hand, are governed by human actions. These actions are only partly rational and predictable, and many of them are responsive to stimuli quite dissociated from the environmental situation. Whether a field is plowed, left fallow, or planted with one crop or another may be governed by land-bank politics, foreign markets, or the latest developments in crossbreeding. In this situation, the major manipulations of the ecosystem, responsive to a relatively small number of decision-making inputs, cause changes so drastic that they overwhelm the smaller and more indirect consequences not only of other decisions (e.g., which fertilizer or insecticide to use) but also of all but the strongest environmental variables.

In landscapes having a high level of domesticity, it becomes more and more certain that the environmental consequences of precipitation management (which in wild landscapes follow natural laws at least potentially knowable) will be less and less subject to natural law and more and more subject to unpredictable human behavior quite unrelated to weather modification.

g. Summary

As the result of painstaking research, weather modification impacts are no longer seen as the horrendous threat they were depicted to be a decade ago (Sargent, 1967), and familiarity has not bred contempt. Rather, it might be said that the environmental problems posed by weather modification are being brought into perspective and that that perspective is giving them the appearance of a familiar landscape, in both the physical and institutional senses. The task now is not that of arming against a suspected enemy but of understanding a potential friend.

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